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THE VITAL LIMIT OF EXSICCATION OF CERTAIN ANIMALS.

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INTRODUCTION.

Water is one of the most important constituents of living matter. The water content of animals varies from 50 to nearly 100 per cent. of the total body weight. All living matter appears to live in water. Not only is this true of the simplest forms of life, the Protozoa and the Protophyta, which are hardly more than naked protoplasm, but it is also true of the more complex organisms where lymph, blood, and sap are found as liquids; the immediate environment of the individual cell. Any change in the amount of water present may interfere with the activities of the cell. Yet it is a familiar fact to zoölogists that many animals will endure considerable exsiccation.

One hundred and fifty years of experimentation has shown that some animals become immobile when gradually dried out, and are apparently dead. This condition Preyer (1891) called "anabiosis." Leeuwenhoek was perhaps the first to observe this phenomenon in 1701. He found that Rotifera and Tardigrada

living in the sand of roof gutters could be completely dried out without losing vitality. Baker (1764) revived nematodes after they had been in a dried state for twenty-seven years. Doyère (1842) found that Tardigrada could endure higher temperatures, as well as extreme exsiccation, without injury and in many cases were able to live even in the absence of oxygen. Semper (1881) tells of experiments with *Apus* and *Cypris* eggs, which he kept in a chest of dried mud for six years. He was able to hatch out larvæ in summer or winter by adding water to the mud. Semper did not believe, however, that the eggs of the many animals that endure extreme exsiccation lose all their water, but that the integument of the egg does not permit the complete removal of water.

Professor W. S. Marshall has kept *Trogoderma* larvæ alive for more than five years in vials without food or water. Wodsedalek (1921) carried out similar experiments with the same species. The larvæ moulted but became smaller after each moult. They did not eat their moulted skins. In Nature's larger laboratory there are many cases of adaptation of animals to a dry environment. Protozoa and other microscopic forms encyst themselves when ponds dry out. Thus they resist in a motionless state the hot dry winds of summer, but revive again in spring when ponds are filled with water. Spores of bacteria are extremely resistant to exsiccation, living for days on dry glass. Desert lizards live in extremely dry places. In fact, a number of animals live in the driest places on earth.

While there are many experiments to show the effects of exsiccation most of them have been with simpler or smaller animals. Because of the microscopic size of these no quantitative results could be obtained. It would seem improbable that an animal can remain active after losing all its water, or that all the water could be removed from an organism without causing death. Thus it is important to study comparatively the amount of water that can be removed from animals without loss of vitality. Schmidt (1918) found that earthworms can revive and apparently become perfectly normal after a loss of 61.8 per cent. of the body weight, or nearly 73 per cent. of the weight of the water contained in the

body. He used the earthworm *Allolobophora foetida* and a desiccator containing calcium chloride. Durig (1901) found that the common European frog would lose 30 to 39 per cent. of the body weight if the drying was slow. Hill (1906) states that if a man loses ten per cent. of his weight in water, he usually dies. Shelford (1913) found in studying the reactions of animals to evaporation that smaller animals died from loss of water much more rapidly than larger. He also states that when the skins of amphibians became dry they did not recover when put into water.

This paper describes the exsiccation of certain animals. Experiments were carried on at the University of Wisconsin under the direction of Professor A. S. Pearse to whom the writer is greatly indebted for many suggestions and criticisms. Professor M. F. Guyer has also given numerous helpful suggestions. Thanks are also due to Dr. H. H. T. Jackson for the identification of the mammals used, and to Drs. J. A. E. Eyser and W. J. Meek for help in the construction of apparatus.

II. METHOD OF DETERMINATION OF THE VITAL LIMIT.

Apparatus.

The apparatus for these experiments consisted of an air-pump, exsiccating jars, filters, and an exsiccating chamber (Fig. 1).

The air-pump was an automatic electric air compressor¹ provided with an air-tank and a pressure gauge. The tank had a capacity of four gallons. A switch controlled the starting and stopping of the motor, whenever the pressure fell to 20 lbs. or rose to 25 lbs. A valve constructed on the air-tank allowed whatever flow of air was deemed necessary. The air-pump was always in the same room with the exsiccating chamber and where only fresh air was pumped and used.

The exsiccating jars (Fig. 1, *P*, *S*) consisted of four glass jars. The first (Fig. 1 *P*) was a 500 cc. Woulff bottle, full of crushed pumice stone, the pieces ranging from 0.5 mm. to 5 mm. in diameter, and about half full of sulfuric acid C.P. The other three jars were the ordinary washing bottles, filled with sulfuric acid C.P. The four jars were connected in series. Air passing

¹ Central Scientific Co. Cat. No. 218, listed as No. 1390.

from the compressed air-tank through a trap to prevent back flow of acid was rendered dry by its passage through the exsiccating jars.

Two filters were arranged. The first (Fig. 1, *Z*), a 100 cc. bottle containing about an equal weight of powdered and granulated zinc. The purpose of this filter was to prevent the passage of sulfuric acid. The second filter (Fig. 1, *G*), consisting of a 500 cc. bottle filled with glass wool, prevented the passage of any physical impurities. Tests of the air were made by allowing the air as it passed out of the exsiccating chamber to bubble through a methyl-orange solution for an hour. There were no indications of sulfuric acid in the air.

The manometer or flow-meter (Fig. 1, *M*) used for the determination of the rate of flow of air into the exsiccating chamber was constructed of glass tubing. A horizontal tube connecting the two ends of a U-tube and having a small aperture between the points of connection allowed the passage of air from the second filter to the exsiccating chamber. The U-tube was partly filled with olive oil, which was used because of its low evaporating coefficient. The passage of air through the horizontal tube increased the pressure on the column on one side thereby lowering the level. The difference of level of the liquid in the U-tube was a measure of the static pressure and was an indicator of the rate of flow of the air passing into the exsiccating chamber. The manometer was accurately calibrated from a gas meter used for such purposes by the department of physiology, University of Wisconsin. A scale was placed behind the U-tube and the rate of flow in cubic centimeters could be read at any time.

A large Whithall-Tatum museum jar (Fig. 1, *C*) was used for the exsiccating chamber. Four holes were drilled through the lid, one for the dry air inlet, one for the air outlet, two for the inlet and outlet tubes to the dew-point apparatus. The lid was fastened by a metal clamp and sealed by a rubber gasket. An outlet tube connected the exsiccating chamber with a small beaker containing sulfuric acid (Fig. 1, *O*). The end of the outlet tube was just far enough below the surface of the acid to indicate by bubbling if the chamber was tightly sealed, and also to prevent back flow of air containing water.

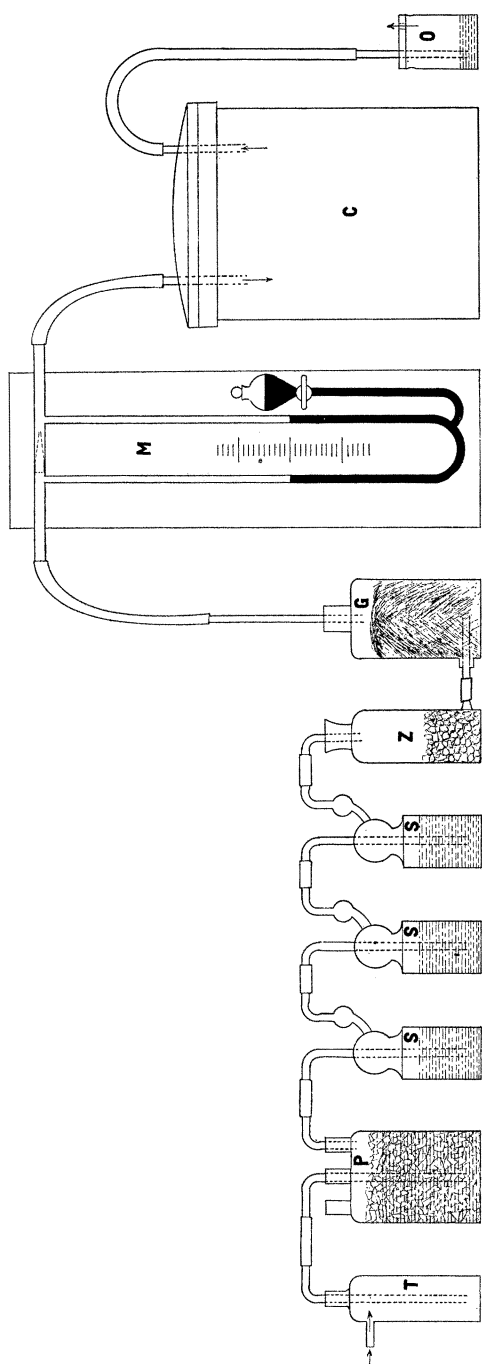


FIG. 1. Plan of apparatus for determining the vital limit of exsiccation of animals. *T*, trap; *P*, pumice stone and sulfuric acid exsiccating jar; *S*, sulfuric acid exsiccating jars; *Z*, zinc filter; *G*, glass wool filter; *M*, manometer; *C*, exsiccating chamber; *O*, outlet.

Plan of Experiments.

The animals used for these experiments, with the exception of the mice, were kept for several days without food; so that their digestive systems were evacuated. They were kept in cages and supplied constantly with water. The mice were kept in cages, and supplied with food and water. All the animals were weighed separately; the earthworms, leeches, and meal worms were weighed and then placed in small flat glass dishes which were covered with cheese cloth. From one to eight dishes were placed in the exsiccating chamber at a time; the salamanders, frogs, snakes, lizards, turtles, and mice were weighed in screen cages and transferred directly to the exsiccating chamber. A screen partition was used to separate the animals when more than one was exsiccated at a time.

The temperature, air-flow in cubic centimeters per minute, and the time were noted on a record card for each individual. The corn or oats fed the mice was weighed and the amount eaten noted each day. The relative humidity was found to vary considerably while animals were in the chamber. With an air-flow of 1,000 cubic centimeters per minute the relative humidity varied from 0 to 10 per cent.¹ The supply of sulfuric acid in the exsiccating jars was renewed whenever there was indication that it had been weakened much by the absorption of water.

After removal from the exsiccating chamber the animals were placed in as normal an environment as could be obtained. The invertebrates were placed on moist filter paper at normal room temperatures. Some individuals were placed in a refrigerator where recovery from exsiccation was more easily accomplished.

The limit of exsiccation was determined by the maximum percentage of water that could be removed from an animal without the loss of vitality. Water was removed from an animal by subjecting it to dry air in an exsiccating chamber (Fig. 1, C). The loss of weight was the means used for the determination of the

¹ By means of absorption tubes containing H_2SO_4 , c. p. connected at the outlet of the exsiccating chamber (Fig. 1, C), not a trace of water was found to pass for a period of 25 hours, providing there was no animal in the exsiccating chamber.

percentage of water lost. Results of these experiments on the vital limit of exsiccation are summarized in Tables I.-XII.

Water Content Determination.

It was thought by the writer to be of interest to ascertain the amount of water normally present in the species that were used in the exsiccation experiments. The water content was determined by drying the animals in a drying oven and weighing at intervals until the weight became constant. The oven was kept at 99° C. The percentage of water in relation to the body weight for several species was as follows: meal worm (*Tenebrio molitor*), 49.8 per cent. (average of 60 individuals); leech (*Placobdella parasitica*), 76.4 per cent. (average of 10 individuals); house mouse (*Mus musculus*), 70.8 per cent. (average of 7 individuals); frog (*Rana pipiens*), 80.8 per cent. (average of 2 individuals). Schmidt (1918) found the water content of the earthworm, *Allolobophora fætida*, to be 84.1 per cent. (an average of 13 individuals).

III. EXPERIMENTAL RESULTS.

Earthworm.

The species used in this experiment was the *Allolobophora chloroticus* (Savigny). The worms were collected near Lake Mendota during the summer of 1919. They were placed between moist filter paper in flat glass jars and kept for several days before using. They were rolled on dry filter paper in order to remove surface moisture and weighed in small flat dishes before being subjected to exsiccation. Several individuals were exsiccated at a time. Individual worms were removed at intervals. Directly following removal from the exsiccating chamber they were placed on moist filter paper for recovery.

When the worms were exsiccated they became contracted, assumed a dark brown color, and lost all mobility. As exsiccation approached the vital limit the worms lost all elasticity of the body and a mucus-like covering was secreted. It was found that worms after exsiccation, if placed in a refrigerator at a temperature of 10° to 14° C., recovered after a greater loss of water than those that were kept at ordinary room temperature. Perhaps

lower temperature retarded bacterial decomposition. Worms Nos. 8-13, and 16-22, inclusive, did not show clitella. Many individuals showing clitella bled considerably. As the clitellum is abundantly supplied with blood vessels, blood effusion probably takes place more readily. Worms also appeared to be killed by infection in some cases.

The results of these experiments, with twenty-two individuals, show: (1) worms were exsiccated up to a loss of 69.6 per cent. of their body weight, or approximately 83 per cent. of the water contained in their bodies, was given up without loss of vitality; (2) lower temperatures were more favorable to the recovery of exsic-

TABLE I.
EARTHWORM, *Allolobophora chloroticus* (Savigny).

No.	Weight.		Condition of Exsiccation.		Results.				Condition of Animal after Exsiccation.
	Initial.	Lost.	Rate of Air-flow, c.c. min.	Deg. C.	Time in Hours.	Survived.	Days Lived.	% Exsiccated.	
1	0.473	0.288	500	28	4' 30"	no	—	61.1	Hard, dry, inactive
2	0.690	0.405	500	28	4' 30"	no	—	42.7	Hard, dry, inactive
3	0.733	0.328	500	28	4' 0"	no	—	44.7	Hard, dry, inactive
4	0.626	0.064	600	30	1' 0"	yes	Indef. ¹	10.2	Active
5	0.570	0.150	600	30	2' 0"	yes	Indef.	26.3	Active
6	0.223	0.144	600	30	3' 0"	no	—	64.6	Inactive, dry, hard
7	0.199	0.139	600	30	3' 0"	no	—	70.0	Inactive, dry, hard
8	1.833	0.870	400	28	2' 30"	no	—	47.5	Inactive, dry
9	0.220	0.119	400	28	2' 30"	no	—	54.1	Inactive, dry
10	0.240	0.149	300	28	1' 30"	yes	2 ³	62.1	Alive, inactive (R) ²
11	0.273	0.190	300	28	1' 45"	yes	4	69.6	Inactive, dry (R)
12	0.171	0.091	300	28	1' 45"	yes	Indef.	54.4	Inactive, dry (R)
13	3.014	0.780	500	27	1' 45"	yes	I	25.9	Active (R)
14	0.590	0.115	500	27	2' 0"	yes	Indef.	19.5	Active (R)
15	2.086	0.351	500	27	2' 40"	no	—	16.8	Inactive, dry (R)
16	2.601	0.443	500	27	3' 10"	yes	I	17.0	Active (R)
17	0.480	0.150	800	27	2' 0"	yes	I	31.2	Active (R)
18	0.686	0.224	800	27	2' 30"	yes	I	32.7	Active (R)
19	0.664	0.195	800	27	3' 0"	yes	I	29.3	Active (R)
20	0.790	0.204	800	27	3' 0"	yes	I	25.8	Active (R)
21	0.645	0.281	800	27	4' 30"	yes	I	42.9	Inactive (R)
22	0.360	0.178	800	27	4' 30"	yes	I	49.2	Inactive (R)

¹ By "Indef." is meant that the animals lived for forty days or more. The exact number of days was not recorded after the fortieth day.

² (R)—revived in refrigerator at 10° to 14° C.

³ Death accidental.

cated worms; (3) worms not showing clitella dried more slowly and endured more exsiccation than those showing clitella.

Leech.

The species used for these experiments was *Placobdella parasitica* (Say) Moore. Specimens were collected from aquaria containing turtles and methods employed were the same as those used for earthworms with the exception that the leeches were kept under water until used. During exsiccation each leech coiled up into a ball-shaped mass containing air, for when they

TABLE II.

LEECH, *Placobdella parasitica* (Say) Moore.

No.	Weight.		Condition of Exsiccation.			Results.			Remarks.
	Initial, gms.	Lost, gms.	Time, Hours.	Deg. C.	Rate of Air-flow, c.c. min.	Survived.	Days Lived.	% Exsiccated.	
1	0.620	0.323	6' 15"	22	1,000	yes	6	52.1	R. (13° C.). Hard, dry, inactive.
2	0.865	0.524	6' 15"	22	1,000	yes	8	60.6	Hard, dry, inactive.
3	0.592	0.403	6' 0"	20	1,000	yes	5	68.1	Hard, dry, inactive.
4	1.470	0.520	8' 0"	20	1,000	yes	Indef.	35.3	Dry, active.
5	0.733	0.403	5' 30"	20	1,000	yes	6	55.0	Hard, dry, inactive.
6	0.542	0.350	8' 0"	20	1,000	yes	Indef.	64.6	Hard, dry, inactive.
7	0.430	0.289	5' 30"	20	1,000	yes	8	67.2	R. (13° C.). Hard, dry, inactive.
8	0.660	0.467	8' 0"	20	1,000	no	—	70.7	Hard, dry, inactive.
9	0.484	0.341	7' 30"	22	1,000	yes	17	70.4	R. (13° C.). Hard, dry, inactive.
10	0.566	0.242	5' 30"	22	1,000	yes	Indef.	57.2	Hard, dry, inactive.
11	0.523	0.349	7' 30"	22	1,000	no	—	66.7	Hard, dry, inactive.
12	1.175	0.540	9' 45"	22	1,000	yes	Indef.	46.0	Dry, flexible.
13	0.554	0.370	6' 15"	22	500	no	—	66.8	Hard, dry, inactive.
14	1.000	0.650	9' 30"	22	500	no	—	65.0	Hard, dry, inactive.
15	0.476	0.326	9' 30"	22	500	yes	4	68.7	R. (13° C.). Hard, dry, inactive.
16	0.331	0.256	9' 30"	22	500	no	—	77.3	Hard, dry, inactive.
17	0.305	0.235	7' 30"	25	1,000	no	—	77.0	R. (13° C.). Hard, dry, inactive.
18	0.320	0.250	7' 30"	25	1,000	no	—	78.1	R. (13° C.). Hard, dry, inactive.
19	0.405	0.285	7' 30"	25	1,000	no	—	70.4	R. (13° C.). Hard, dry, inactive.
20	0.425	0.313	7' 30"	25	1,000	no	—	73.6	R. (13° C.). Hard, dry, inactive.

were dropped into water after exsiccation small air bubbles arose as the leeches uncoiled. After extreme exsiccation the leeches became hard; the skin dry; all mobility and elasticity were lost; and a mucus secretion enveloped the body, as was the case with the earthworms. During recovery the body, posterior to the twelfth segment, became swollen and was apparently inactive. The anterior part of the body remained active. The posterior part of the body became swollen to twice its natural size and softened. After a few days it broke open and the animal apparently bled to death. Leeches usually showed signs of recovery within an hour after removal from the exsiccation chamber to water.

The results of these experiments, with twenty individuals, show: (1) leeches were exsiccated to 70.4 per cent. of their body weight, or approximately 92 per cent. of the water contained in the body was given up, without loss of vitality; (2) lower temperatures were more favorable to the recovery of the exsiccated leeches.

Meal Worm.

The meal worm, the larva of *Tenebrio molitor* Linn., was used. The methods employed were the same as with the earthworm. It was very difficult to tell when the vital limit of exsiccation was reached as the meal worms were inactive for the greater part of the time while in the exsiccating chamber. One meal worm lost a greater percentage of body weight than the average percentage of water contained in the body. The body of the meal worm contains much fat. It is probable that metabolic water was derived from this fat during exsiccation. The body of a meal worm always became considerably compressed during exsiccation.

The results of these experiments, with ten individuals, show: (1) meal worms were exsiccated to 52.6 per cent. of their body weight without loss of vitality; (2) the weight lost was greater than the average weight of water contained in the body; (3) the chitinous integument is probably a factor in offering resistance to evaporation. The meal worms endured exsiccation for a considerable length of time.

TABLE III.

MEAL WORM, *Tenebrio molitor* Linn.

No.	Weight.		Condition of Exsiccation.			Results.			Condition after Exsiccation.
	Initial.	Lost.	Rate of Air-flow, $\frac{\text{c.c.}}{\text{min.}}$	Temp. °C.	Time, Hours.	Survived.	Days Lived.	% Exsiccated.	
1	0.223	0	500	22	4	yes	60+	0	Normal.
2	0.245	0	500	22	9	yes	60+	0	Normal.
3	0.190	0.002	500	22	49	yes	60+	1.0	Normal.
4	0.152	0.039	500	22	508	yes	60+	26.3	Inactive.
5	0.190	0.100	500	22	1,084	yes	2+	52.6	Inactive.
6	0.206	—	500	20	1,130	no	—	—	
7	0.195	0.185	500	20	70	yes	60+	5.1	Normal.
8	0.218	—	500	20	1,130	no	—	—	
9	0.190	0.007	500	20	70	yes	60+	3.7	Normal.
10	0.247	—	500	20	1,130	no	—	—	

Amphibia.

Two species of the Amphibia were used: the leopard frog, *Rana pipiens* (Schreber), and the salamander, *Ambystoma punctatum* (Baird). The frogs and salamanders were collected at various times during the year and were kept in a vivarium until used. Two or three specimens were exsiccated at a time, but individual records were kept. After extreme exsiccation neither frogs nor salamanders showed signs of life. There was not a reflex action to indicate that they were alive, though the temperature was 20° to 22°C. After they had been placed in water, following removal from the exsiccation chamber, during an hour they had always revived enough to swim. During one experiment weights were taken of a salamander to show how soon the weight lost could be regained. Within 24 hours the animal had regained 97.7 per cent. of the weight lost by the body during exsiccation.

The results of the experiments with salamanders, with nine individuals, show: (1) salamanders were exsiccated to 47 per cent. of their body weight without loss of vitality; (2) salamanders gave up water easily and regained water quickly when returned to their natural environment.

The results of the experiments with frogs, with six individuals, show: (1) frogs were exsiccated to 41.0 per cent. of their body weight, and that 50 per cent. of the water contained in their bodies was given up without loss of vitality.

TABLE IV.

SALAMANDER, *Ambystoma punctatum* Baird.

No.	Weight.		Condition of Exsiccation.			Results.			Condition and Behavior after Exsiccation.
	Initial, gms.	Lost, gms.	Deg. C.	Rate of Air-flow, $\frac{c.c.}{min.}$	Time, Hours.	Survived.	Days Lived.	% Exsiccated.	
1	27.030	4.230	20	1,200	9' 0"	yes	Indef.	15.6	Normally active.
2	37.500	4.300	18	1,000	13' 30"	yes	Indef.	11.5	Normally active.
3	44.620	4.520	14-17	600	23' 0"	yes	Indef.	10.1	Normally active.
4	38.600	4.800	14-17	600	23' 0"	yes	Indef.	12.4	Normally active.
5	36.600	13.760	22	800	51' 0"	yes	Indef.	37.6	Active, dried up appearance.
6	44.050	10.580	22	800	31' 0"	yes	Indef.	24.0	Normally active.
7	23.370	11.170	8-20	500	188' 0"	no	—	47.9	Dead, hard, dry.
8	35.550	15.750	8-20	500	144' 0"	yes	Indef.	44.4	Inactive, dry, no signs of life.
9	38.450	18.070	20	600	116' 0"	yes	Indef.	47.0	Inactive, dry, no signs of life.

TABLE V.

FROG, *Rana pipiens* Schreber.

No.	Weight.		Condition of Exsiccation.			Results.			Condition after Exsiccation.
	Initial, gms.	Lost, gms.	Rate of Air-flow, $\frac{c.c.}{min.}$	Deg. C.	Time, Hrs.	Survived.	Days Lived.	% Exsiccated.	
1	38.100	4.300	400	26	7	no	—	11.3	Inactive, dead.
2	37.000	3.900	400	26	7	yes	20+	10.5	Active.
3	22.800	9.340	1,000	22	33	yes	30+	41.0	Skin dry, apparently dead.
4	22.305	9.795	1,000	21	32	no	—	43.5	Inactive.
5	16.460	5.930	1,000	20	24	yes	30+	36.0	Apparently dead, skin dry.
6	18.230	8.270	1,000	21	31	no	—	45.6	Inactive.

Reptilia.

Five reptiles were used: the garter snake, *Thamnophis radix* (Baird); the painted turtle, *Chrysemys marginata* Agassiz; the American chameleon, *Anolis carolinensis* Cuvier; the horned "toad," *Phrynosoma cornutum* Harlan; the desert lizard, *Sceloporus spinosus floridanus* Wiegmann. Only one snake was exsiccated and it died before removal from the exsiccation chamber.

The turtles were collected from the Madison lakes and were kept in a vivarium until used. As the shell of a turtle adds considerable weight to the body, the water content is not as high, and exsiccation cannot be carried as far. The turtles were revived from exsiccation by removal to an aquarium. Turtle No. 1 lost all activity after exsiccation. Its eyes were sunken, and the skin became very dry. The turtle appeared to be dead, but when cut open its heart was still beating.

The chameleons, horned "toads," and desert lizards were procured from a collector in Texas. The same method of exsiccation was employed as in the preceding experiments. No food was given. The chameleons were exsiccated at a comparatively rapid rate. Their skin became shrivelled, and eyes sunken. The exsiccation of the horned "toads" and desert lizards was very slow. The dry air apparently had no injurious effect upon them until a few days previous to death. At that time they gasped

TABLE VI.

TURTLE, *Chrysemys marginata* Agassiz.

No.	Weight.		Condition of Exsiccation.			Results.			Condition after Exsiccation.
	Initial.	Lost.	Rate of Air-flow, c.c. min.	Deg. C.	Time. Hrs.	Survived.	Days Lived.	% Exsiccated.	
1	347.500	114.960	700	20	288	yes	1	33.1	Heart beating normally.
2	281.500	94.000	1,000	20	257	no	—	33.3	Inactive, dead.
3	334.000	94.800	1,000	20	304	yes	Indef.	28.4	Inactive, few signs of life.

continually and breathing seemed forced. As no food was given them, starvation was probably a factor in producing death. It is very remarkable that these animals can endure exsiccation for so long a time without food or water, in perfectly dry air. They lived for nearly four months, apparently with no discomfort. It is easy to understand how they can live in desert areas where many other animals would perish.

TABLE VII.

CHAMELEON, *Anolis carolinensis* Cuvier.

No.	Weight.		Condition of Exsiccation.			Results.			Condition after Exsiccation.
	Initial.	Lost.	Rate of Air-flow, c.c. min.	Temp. ° C.	Time, Hours.	Survived.	Days Lived.	% Exsiccated.	
1	2.110	0.205	1,000	20	17	no	—	10.8	Active.
2	2.360	0.880	1,000	20	184	yes	40+	28.8	
3	1.910	0.885	1,000	20	186	yes	40+	46.3	
4	1.315	—	1,000	20	48	no	—	—	Active.
5	2.190	0.837	1,000	20	168	no	—	36.9	
6	1.220	0.350	1,000	20	195	yes	40+	28.8	

TABLE VIII.

DESERT LIZARDS, *Phrynosoma cornutum* and *Sceloporus spinosus*.

Species.	No.	Weight.		Condition of Exsiccation.			% Exsiccated.	Survived.
		Initial.	Lost.	Rate of Air-flow, c.c./min.	Temp., ° C.	Time in Days.		
<i>P. cornutum</i> ..	1	31.510	10.640	800	21	119	33.8	no
" " ..	2	55.850	10.680	800	21	114	19.1	no
" " ..	3	41.250	—	800	21	22	—	no
<i>S. spinosus</i> ...	1	38.300	11.340	800	21	86	29.6	no
" " ...	2	9.400	4.500	800	21	62	47.8	no

The results of these experiments show: (1) Turtles were exsiccated to 33.1 per cent. of their body weight without loss of

¹ This specimen was killed after exsiccation for an examination of the anal bladder.

vitality ; and chameleons were exsiccated to 46.3 per cent. of their body weight without loss of vitality. (2) Horned "toads" and desert lizards were exsiccated to 33.8 per cent. and 47.8 per cent. of their body weight, respectively, before death occurred. (3) Horned "toads" and desert lizards endured exsiccation and starvation for 119 and 86 days, respectively, before death occurred. (4) Reptiles are apparently better fitted to resist exsiccation than any other group of animals experimented upon.

Mammalia.

As representatives of the mammals, three rodents were used: the house mouse, *Mus musculus* (Linn.) ; the wood mouse, *Peromyscus leucopus noveboracensis* (Fischer) ; and the meadow mouse, *Microtus pennsylvanicus* (Ord.). The mice were caught in traps and kept in cages in a vivarium with food and water before them constantly. During exsiccation corn and oats were fed and the amount eaten determined by subsequent weighing. Mice remained active until the vital limit of exsiccation was apparently reached and then died quickly if not removed to a suitable environment. The mice became very nervous after subjection to the dry air for a few days but became drowsy as the vital limit was approached.

TABLE IX.

WOOD MOUSE, *Peromyscus leucopus noveboracensis* (Fischer).

No.	Weight.		Condition of Exsiccation.			Food.	Results.			Condition of Animal after Exsiccation.
	Initial.	Lost.	Rate of Air-flow, c.c. min.	Temp. ° C.	Time in Hours.		Survived.	Days Lived.	% Exsiccated.	
1	14.120	4.900	1,000	20	144	10	no	—	34.7	Dead.
2	15.630	—	1,000	20	118	10	no	—	—	Dead.
3	11.790	3.440	1,000	20	75	3	yes	Indef.	29.2	Active.
4	12.230	3.760	1,000	21	77	20	yes	Indef.	30.7	Active.

The results of the experiments with mice, summarized in Tables IX.-XI., show: (1) The house mouse was exsiccated to

24.2 per cent. of its body weight, or about 34 per cent. of the water contained in its body was given up, without loss of vitality.

(2) The wood mouse was exsiccated to 30.7 per cent. of its body

TABLE X.

MEADOW MOUSE, *Microtus pennsylvanicus* (Ord.).

No.	Weight.		Condition of Exsiccation.			Food.	Results.			Condition of Animal after Exsiccation.
	Initial.	Lost.	Rate of Air-flow, c.c. min.	Temp. ° C.	Time in Hours.		Survived.	Days cated.	% Exsiccated.	
1	32.110	9.930	1,000	20	48	2	yes	2	30.8	Active.
2	21.780	10.450	1,000	20	54	2	yes	1	48.0	Slightly active.
3	31.460	7.580	700	19	48	3	yes	Indef.	24.1	Active.
4	28.830	9.450	1,000	20	68	3	yes	Indef.	32.1	Active.

TABLE XI.

HOUSE MOUSE, *Mus musculus* Linn.

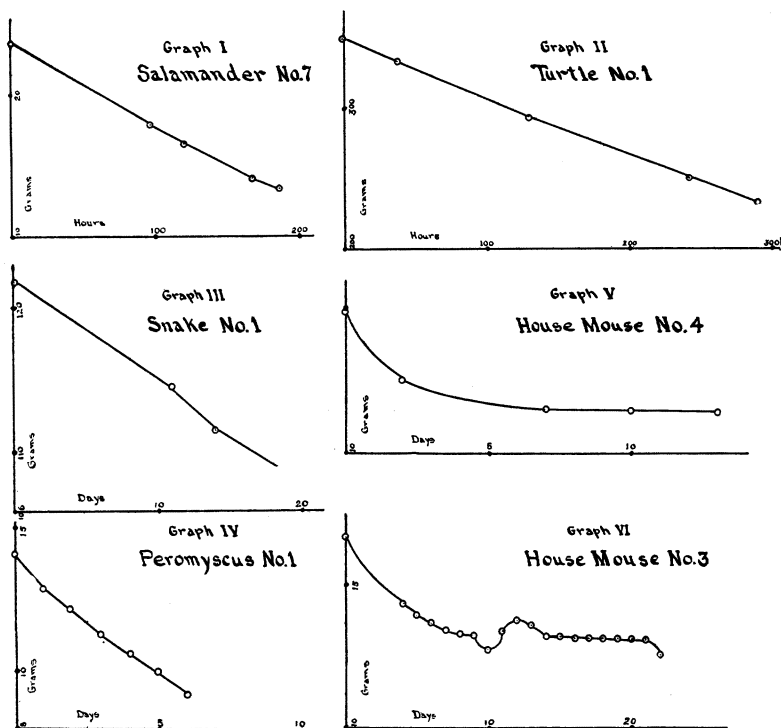
No.	Weight.		Condition of Exsiccation.			Food.	Results.			Behavior, Etc.
	Initial, gms.	Lost, gms.	Time, Hrs.	Deg. C.	Rate of Air-flow, c.c. min.		Survived.	Days Lived.	% Exsiccated.	
1	9.530	1.140	12	20	500	0	yes	Indef.	12	Normal.
2	13.820	3.200	65	20	600	0	1	1	23.3	
3	16.540	3.980	263	20	1,000	60	1	1	24.1	
4	14.860	3.460	308	20	1,000	25	1	1	23.3	
5	14.300	1.900	383	20	500	30	yes	Indef.	13.3	Inert, gasping for breath, at removal.
6	16.320	4.590	145	20	1,000	15	yes	—	28.1	Active.
6	16.320	5.735	191	20	1,000	15	no	—	35.1	Dead.
7	20.050	2.930	72	21	1,000	20	yes	Indef.	14.6	Active.
8	15.230	3.780	270	21	1,000	40	yes	Indef.	24.2	Active.

¹ These mice were dead when removed and the weight recorded is the last weight made before they died. As the exact time of death was not known, no weights of the dead mice were taken. The last weight was taken in each case from 12 to 24 hours before death.

weight without loss of vitality. (3) The meadow mouse was exsiccated to 32.1 per cent. of its body weight without loss of vitality.

Graphs.

The graphs shown in Fig. 2 represent the loss of water during exsiccation for intervals of time. It will be noted that in the graphs, with the exception of the house mouse, the water lost for intervals of time is constant. In the case of the house mouse, however (graphs V., VI.), the downward curve indicates a rapid



loss of water for the first few days, it then straightens and is nearly horizontal until death of the mouse occurs.¹ These facts indicate a resistance in the house mouse to evaporation—a resist-

¹ The irregularities in Graph VI. for the ninth to the twelfth days are due to the absence of food the ninth day and the excess eaten the following day.

ance that inhibits evaporation beyond a certain limit. Obviously, a mouse got some water from the corn eaten. The corn was tested and was found to contain less than eight per cent. water. Thus the amount of water obtained from the small amount of corn eaten would be too small to supply the daily loss. Probably metabolic water plays a part in replacing that evaporated.

DISCUSSION.

The chief functions of water in animals are: (1) to dissolve nutrients, (2) to serve as a medium for their distribution, (3) to aid excretion by removing waste products from cells, and (4) to control the body temperature. Water is the most abundant constituent of the living organism and is essential to all life. The relative amount of water contained in animals depends upon the kind of organism, the period of growth, and the nature of food, environment, and activities.

In these experiments an attempt has been made to determine the effect of a dry environment upon the amount of water present in organisms, and the effect of exsiccation upon the vital activities. There is need of more complete knowledge of the effects of exsiccation and though the present paper does not settle all problems relating to the loss of water by animals, it adds certain facts that may be of general interest. The different types of animals were subjected to comparable conditions.

It is apparent that the water content of different species varies greatly. The relative amount of water that may be lost and the relative length of time that animals can endure exsiccation also varies considerably. The important factors which limit such variations are: the kind of animal, the size of the animal, the integument, the general metabolism, and the elimination of body wastes.

The results of the writer's experiments apparently support the statements of Babcock (1912), that the need for water is much less for animals that excrete uric acid than those that excrete urea, since uric acid, being practically insoluble in the body fluids, is not as poisonous as urea, and is excreted in solid form with the loss of very little water. Weese (1912) has shown that the excretions of horned "toads" are largely uric acid. This is probably true for many insects.

The migration of the amphibians from water to land is regarded as a very important event in the evolution of animals. Closely associated with the adoption of a terrestrial mode of existence by the amphibians is a change in the water content (Oswald, 1917). Before the frog takes to land, for instance, it consists of ninety-three per cent. water. When it becomes a land animal much of its water is lost. During its terrestrial life a frog lives in moist places and when subjected to extreme dryness loses much of its water. In the writer's experiments as much as forty-one per cent. of the body weight, or fifty per cent. of the water contained in the body, was given up without loss of vitality. As water is given up so readily, areas where the evaporation rate is high would be generally unfavorable for frogs and for amphibians in general. Shelford (1913) has shown that amphibians, and other animals as well, react to evaporation gradients and concludes that the evaporating power of the air is probably the best index of the suitability of conditions for land animals.

Water does not evaporate from animals as it does from a surface of free water. Even those animals in which the integument permits little apparent evaporation, are able in some way to retard evaporation of water. To test this point a small stender dish containing 30 cc. of distilled water was subjected to the same conditions as a salamander during exsiccation. The area of surface exposed including skin, mouth, and lungs of a salamander weighing thirty-five grams, was estimated to be 121 square centimeters. The average amount of water lost from the dish having an area of 22.9 square centimeters was 4.520 grams per day. The average loss from salamanders was 0.770 grams per day. Of the animals used in the experiments described in this paper the salamander showed the most rapid rate of evaporation, yet the rate of evaporation from an exposed surface of free water was thirty times as great.

GENERAL SUMMARY.

1. Animals in general are very susceptible to loss of water in atmospheres of low relative humidity.
2. Animals may lose a very large percentage of the water contained in their bodies without loss of vitality.

3. The amount of water that can be lost by animals without fatal results is in general greater in the less complex animals.

4. The length of time that animals can endure atmospheres of low relative humidity in general depends primarily upon the kind of integument and secondarily upon the proportion of the body surface to the body mass.

5. Metabolism of an organism is an important factor in its resistance to exsiccation.

TABLE XII.

COMPARATIVE RESULTS OF EXSICCATION EXPERIMENTS.

Species.	Table.	Per Cent. Exsiccated of		Time Required.
		Body Weight.	Water Content.	
<i>Allolobophora chloroticus</i>	I.	69.6	83	105 mins.
<i>Placobdella parasitica</i>	II.	70.3	92	450 mins.
<i>Tenebrio molitor</i>	III.	52.6	105	1,084 hours
<i>Ambystoma punctatum</i>	IV.	47.0	—	116 hours
<i>Rana pipiens</i>	V.	41.0	50	33 hours
<i>Chrysemys marginata</i>	VI.	33.1	—	288 hours
<i>Anolis carolinensis</i>	VII.	46.3	—	186 hours
<i>Phrynosoma cornutum</i>	VIII.	33.8	—	119 days
<i>Sceloporus spinosus</i>	VIII.	47.8	—	86 days
<i>Peromyscus leucopus</i>	IX.	30.7	—	77 hours
<i>Microtus pennsylvanicus</i>	X.	32.1	—	68 hours
<i>Mus musculus</i>	XI.	24.2	34	270 hours

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